AD-A163 170 FIELD TESTS OF THE KINETIC FRICTION COEFFICIENT OF SEA ICE(U) COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH J TATINCLAUX ET AL OCT 85 CRREL-85-17 1/1

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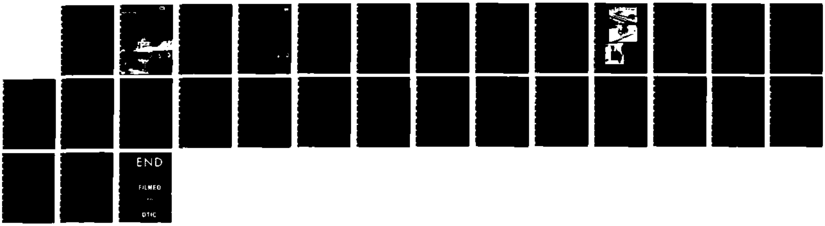

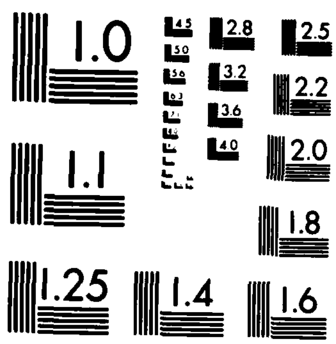

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CRREL
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Field tests of the kinetic friction coefficient of sea ice

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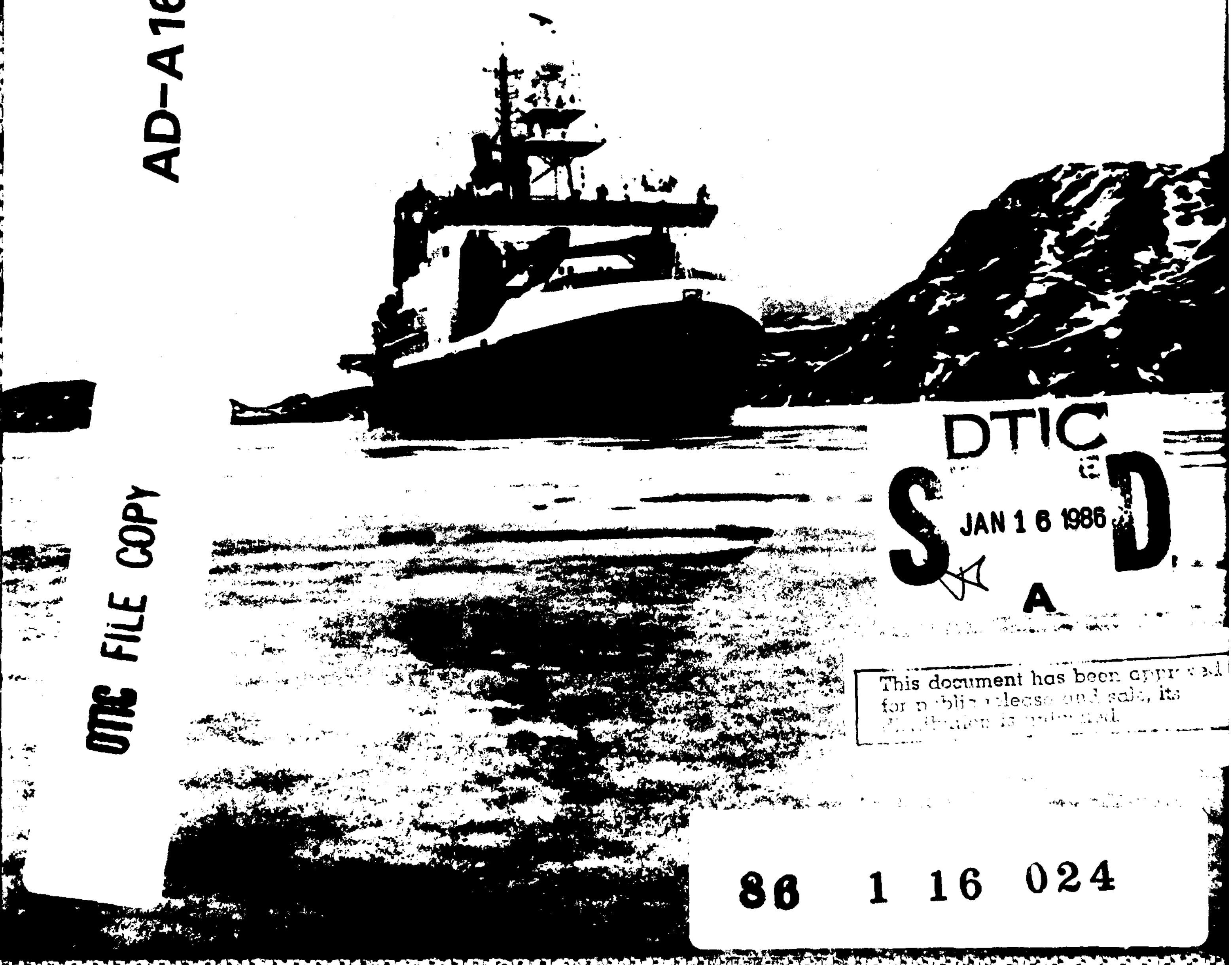

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CRREL Report 85-17

October 1985

(12)

Field tests of the kinetic friction coefficient of sea ice

Jean-Claude Tatinclaux and David Murdey

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER
CRREL Report 85-17

2. GOVT ACCESSION NO.
AD-A163 170

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
FIELD TESTS OF THE KINETIC FRICTION COEFFICIENT OF SEA ICE

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Jean-Claude Tatinclaux and David Murdey

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Army Cold Regions Research and
Engineering Laboratory
Hanover, New Hampshire 03755-1290

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE
October 1985

13. NUMBER OF PAGES
26

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Friction
Ice
Kinetic friction coefficient
Sea ice

(mu sub k)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of tests of the ice friction coefficient μ_k carried out during the May 1984 expedition of the F.S. *Polarstern* off the coast of Labrador. The test surfaces were Inerta-160-coated steel plates and bare steel plates, hand roughened and sandblasted. The main findings of the studies were: 1) columnar and granular sea ice showed no significant differences in friction coefficient; 2) for columnar ice, μ_k was independent of ice crystal orientation with respect to test surface; 3) μ_k was independent of normal pressure applied on ice sample; 4) μ_k initially decreased with increasing relative velocity between the ice sample and the test surface and reached a steady value at

20. Abstract (cont'd).

higher speeds; 5) μ_k increased with increasing surface roughness; 6) a wetting surface exhibited a higher friction coefficient than a non-wetting surface of the same or even higher roughness average.

PREFACE

This report was prepared by Dr. Jean-Claude Tatinclaux, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, and Dr. David Murdey, Assistant Director, Institute for Marine Dynamics, National Research Council of Canada. The study was funded as part of an In-house Laboratory Independent Research project.

This report was reviewed by James Wuebben and Jon Zufelt of CRREL. The authors express their gratitude to Dr. Joachim Schwarz, Hamburgische Schiffbau Versuchsanstalt, Chief Scientist of the May 1984 scientific expedition aboard the F.S. *Polarstern*, for inviting them to participate in the expedition.

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FIELD TESTS OF THE KINETIC FRICTION COEFFICIENT OF SEA ICE

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INTRODUCTION

Among the projects of the scientific program of the F.S. *Polarstern* expedition of May 1984 along the coast of Labrador, Canada, was the measurement of the kinetic friction factor between various surfaces and sea ice samples collected at the site of the ship trials. The surfaces included a steel sheet coated with Inerta 160 to represent the ship hull, and bare steel sheets of two roughnesses. The latter had previously been tested at CRREL with urea-doped ice, which is used as model ice in tests of icebreakers and other structures (Forland and Tatinclaux 1984). A friction test table was specially constructed by the Hamburgishe Schiffbau Versuchsanstalt (HSVA), the organization leading the expedition, and was instrumented on board the *Polarstern*. The ice samples used in the friction tests were cut from two large ice blocks gathered at the trials site, primarily Hebron Fjord; samples from the same blocks were used in two other projects, which were studies of ice structures (Gow 1984) and ice strength properties (Timco and Frederking, in prep.).

TEST PROCEDURE

Test apparatus

The kinetic friction coefficient of ice μ_k was calculated from the ratio $T/(N+W)$, where T is the tangential force required to hold stationary an ice sample of weight W subjected to a normal load N on a horizontal surface moving at a constant velocity V (Fig. 1).

The friction table built by HSVA for these tests is shown in Figure 2. It consisted of a 2.5- × 1-m platform traveling over a 5.5-m-long frame made of rectangular aluminum channels. The platform was pulled by a continuous chain driven by a 2-hp, variable speed, reversible electric motor, the speed and direction of which were controlled by a single-turn potentiometer. The maximum usable speed of the test table was approximately 30 cm/s, which corresponded to only about 40% of the maximum motor speed. Because of the coarseness of the speed adjustment, it was not possible to repeat a given speed exactly.

Four threaded screws, one at each corner of the support frame, served as support legs and were used to level the moving table. A carpenter's level was used before and during each series of friction tests to ensure that the moving table was horizontal in both the longitudinal and transverse directions.

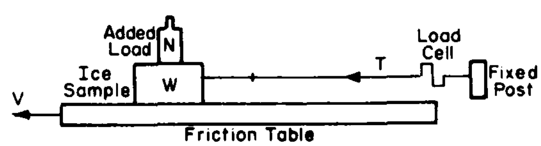
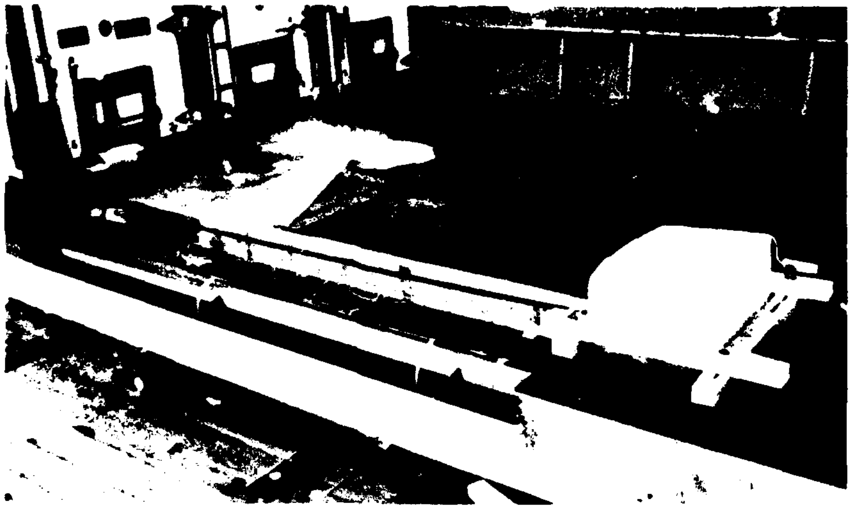
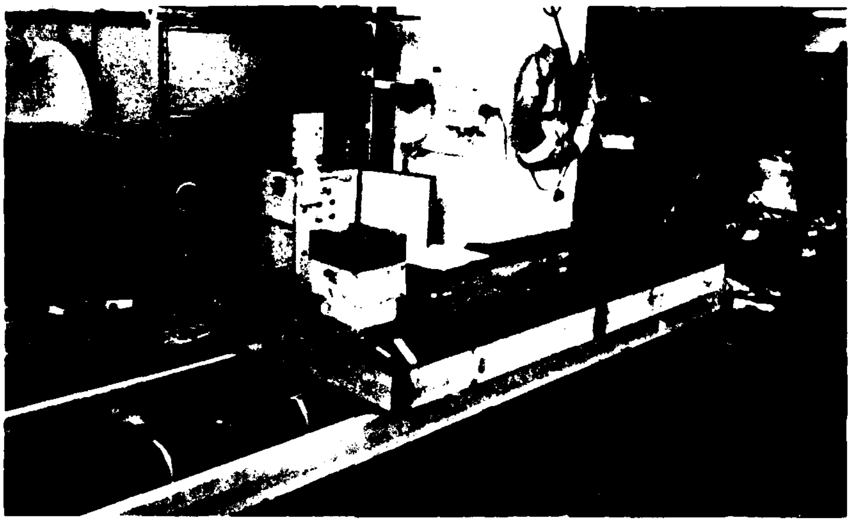


Figure 1. Diagram of friction apparatus.





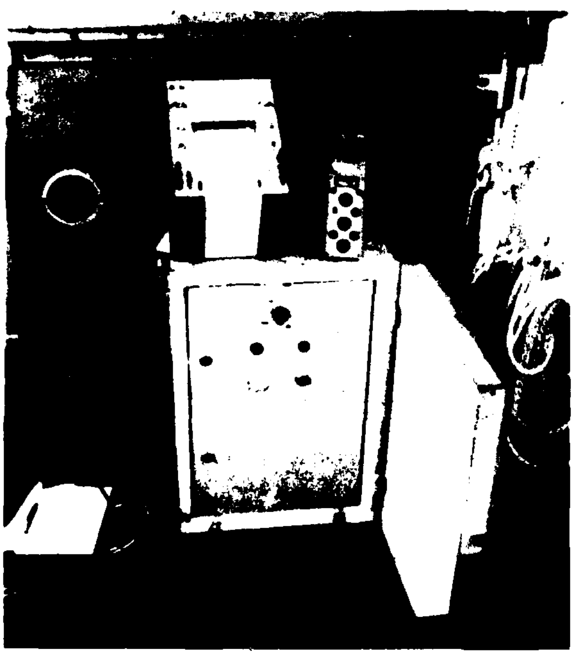


Figure 2. Views of friction table.

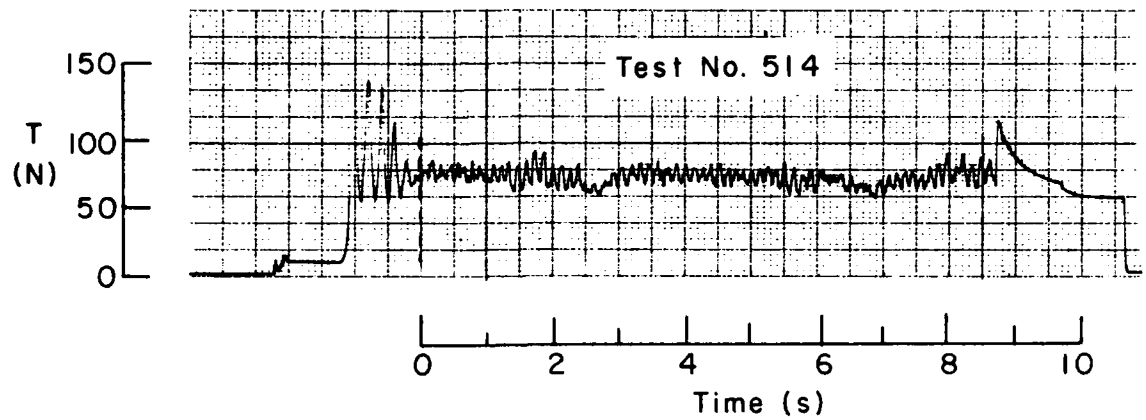


Figure 3. Typical friction force records.

A 450-N-capacity load cell was mounted to one end of the frame and connected to the sample holder by a torsionless wire. The load cell was connected to a Vishay power supply and balancing circuit, with its output recorded on a two-channel chart recorder. The load cell was calibrated before and after each series of tests. Since the velocity displacement transducer brought for velocity measurement was damaged during transport, the table velocity was determined by measuring with a stopwatch the time needed to cover a distance of 1.5 m.

Typical force records from the load cell are shown in Figure 3. The average force measured by the load cell for each test was later determined by measuring the area below the chart trace with a planimeter.

Since the tests were made aboard ship, they could be made only when the ship was at rest and out of the sun to avoid heating of the test surface. A few early tests were carried out in the daytime, but the majority of them were performed in the evening or at night after the ship trials had been completed and the ship was parked for the night. This prevented vibration from the engines from being transmitted to the load cell through the ship structure.

Test surfaces

The test table was initially supplied with a steel plate freshly coated with Inerta 160. Once the tests on this surface were completed, the plate was hand roughened for subsequent tests by 36-grit sandpaper. In addition a test series was conducted on two abutting 1.2- × 0.30-m steel plates, one of which had been roughened with sandpaper and the other sandblasted. These steel plates had been used in friction tests with urea ice grown in the CRREL ice model tank (Forland and Tatinclaux 1984, 1985). The roughness averages R of these surfaces were measured with a Taylor–Hobson Surtronic 3 profilometer, with the following results:

Initial Inerta-coated steel:	$R = 0.97 \pm 0.34\ \mu m$
Roughened Inerta-coated steel:	$R = 3.9 \pm 0.8\ \mu m$
Roughened bare steel:	$R = 1.1 \pm 0.2\ \mu m$
Sandblasted bare steel:	$R = 7.1 \pm 0.7\ \mu m$.

Ice samples

Two types of ice were tested. The first had a granular structure and was tested only with the initial Inerta surface. The second ice was columnar with a horizontal *c*-axis. The ice structure characteristics were described by Gow (1984) and the strength properties by Timco and Frederking (in prep.). With the columnar ice, tests were carried out for the three possible crystal orientations relative to the friction table: vertical columnar crystals perpendicular to the table and horizontal crystals parallel and perpendicular to the direction of motion of the table. These orientations are depicted in Figure 4 and denoted a, b and c, respectively.

In the tests with the Inerta-coated steel plate, the ice samples had approximate dimensions of 0.30×0.30×0.30 m. These dimensions were reduced to about 0.20×0.20×0.20 m for the tests on the narrower bare steel plates. The ice samples, cut from a large ice block, were first stored in a coldroom at -10°C and then at -2°C one day before testing. They were brought on deck near the friction table a few hours before testing so that they would reach thermal equilibrium with the atmosphere.

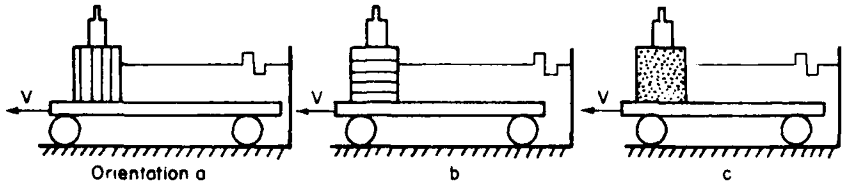


Figure 4. Relative orientations of columnar ice crystals.

Table 1. Summary of test conditions.

Test no.	*Type of ice*	*No. of ice samples*	*Added normal load (N)*	*Crystal orientation*	*Test surface*	*Roughness (μm)*	*Surface condition*	*Air temp. (°C)*	*Velocity range (cm/s)*	*Table of results*
201-221	Granular	7	824	—	Initial Inerta-coated plate	0.97	Dry	~ -0.1	3-20	A3
301-320	Columnar	1	824	a,b	Initial Inerta-coated plate	0.97	Wet	~ 8	~ 12	A1
321-335	Columnar	2	824	a,b	Initial Inerta-coated plate	0.97	Wet	7 to 10	4-30	A5
401-450	Columnar	4	824	a,b,c	Initial Inerta-coated plate	0.97	Dry	-1 to 1.5	2-30	A4
501-563	Columnar	4	824	a,b,c	Roughened Inerta-coated plate	3.8	Dry	-2 to -1	3-30	A6
564-599	Columnar	2	422	a,b,c	Roughened Inerta-coated plate	3.8	Dry	~ 0	3-30	A7
601-610	Columnar	1	804	a	Roughened Inerta-coated plate	3.8	Dry	~ -1	~ 10	A2
701-774	Columnar	4	608	a,b,c	Bare steel plates	1.1 and 7.1	Dry	~ -2.5	3-30	A9
801-836	Columnar	2	608	a,b,c	Bare steel plates	1.1 and 7.1	Wet	~ 0.5	3-30	A10
837-873	Columnar	2	608	a,b,c	Roughened Inerta-coated plate	3.8	Wet	~ 0.5	3-30	A8

Test program

The experiments were designed to study the effects of variations in the following parameters on the kinetic friction coefficient:

1. Type of ice (granular or columnar)
2. Wear in the ice sample
3. Relative crystal orientation (in the case of columnar ice)
4. Relative velocity between the ice and the test surface
5. Normal pressure
6. Type and roughness of test surface (Inerta-coated steel at two roughnesses and bare steel at two roughnesses)
7. Water lubrication (tests were first made on dry surfaces and later on the same surfaces wetted with seawater).

The ambient temperature θ, which could not be controlled, might also have had an effect. However, the majority of the tests were conducted at air temperatures between -2° and 1°C, so there was little melting of the ice. In only one series of tests, conducted at an air temperature of 8–10°C, did significant melting occur; the ice in this series of tests was considered to have a wetted surface.

The test conditions are summarized in Table 1. A total of 362 friction tests were made using 7 granular ice samples and 22 columnar ice samples.

RESULTS AND DISCUSSION

The test results are listed in Appendix A, where conditions specific to each test are indicated.

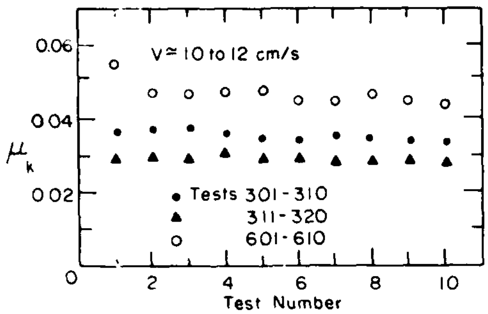


Figure 5. Effect of wear on friction coefficient.

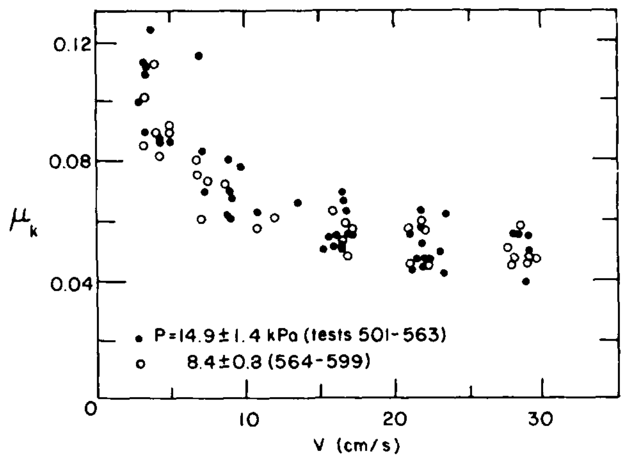


Figure 6. Effect of normal pressure on μ_k (columnar ice on dry, roughened, Inerta-coated plate).

Effect of wear of ice sample

To determine how many friction tests could be safely made with the same ice surface without noticeably changing the friction coefficient, three series of ten successive, nominally identical tests were made. The first two series of wear tests (no. 301-320, Table A1) were made with the same columnar ice sample on wet, smooth, Inerta-coated steel with crystal orientations a and b. The third test series (no. 601-610, Table A2) was made with an ice sample (orientation a) on roughened, Inerta-coated steel under dry conditions.

The test results are plotted in Figure 5 as the friction factor μ_k vs test number. For smooth, Inerta-coated steel there was no significant variation in μ_k between the first and last tests. For roughened, Inerta-coated steel the first test gave a higher friction factor than the following tests, which all produced nearly identical values of μ_k.

On the basis of these results we decided that in the subsequent test series, five to six tests (covering five different velocities) could be performed with the same ice sample and orientation. When repeating the same nominally identical series of five or six tests with different ice samples, we also decided to randomly vary the velocity sequence, and for roughened surfaces the last test in the series was usually made at nearly the same velocity as the first.

Effect of normal pressure

Most laboratory and field data on ice friction coefficients published in the open literature have indicated no detectable influence of normal pressure on μ_k. One series of tests was nevertheless made to verify these observations. A series of tests on roughened, Inerta-coated steel (no. 501-563, Table A6), made with the usual normal load corresponding to a normal pressure of 14-18 kPa, was followed immediately by a second series of tests (tests no. 564-599, Table A7), conducted under identical conditions except that the added normal load was halved, yielding a normal pressure of 7-10 kPa. The results (Fig. 6) show no detectable effect of normal pressure on μ_k.

Effect of velocity, crystal orientation and surface conditions

Figures 7-14 present the results of each series of tests for the conditions of ice type, surface type and roughness and surface condition. There is no apparent effect of ice type (Fig. 7) and no apparent effect of the orientation of the ice crystals with respect to the test surface. For the smooth, Inerta-coated surface, the friction coefficient μ_k is independent of the velocity V, but for the roughened, Inerta-coated surface and both bare steel surfaces, μ_k is an initially rapidly decreasing function of V and tends toward a constant value at higher speeds.

The scatter in the data points increases with increasing roughness (for example, compare Figure 7 with Figure 9 for dry, Inerta-coated steel and Figure 11 with Figure 13 for the dry steel plates). The scatter is also greater when the test surface is wetted rather than dry, especially for the bare steel plates (shown by comparison of Figure 11 with Figure 12 for the roughened plate and Figure 13 with Figure 14 for the sandblasted steel plate). On the sandblasted steel the ice sample sometimes experienced a severe jerking motion, particularly when the surface was wet. Once started, the motion could not be controlled by temporarily holding the sample. This jerky motion never occurred with the Inerta-coated plate, and only occasionally on the roughened steel plate, where it usually could be quickly stopped by holding and immedi-

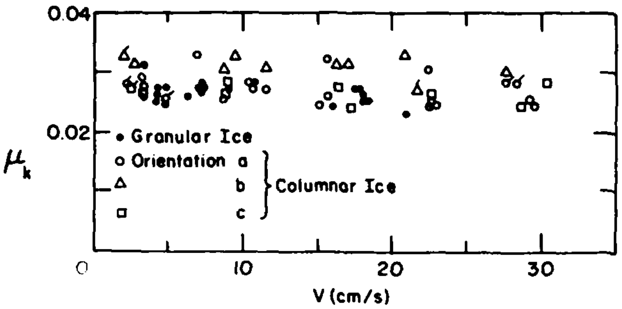


Figure 7. Effect of ice type and crystal orientation (dry, smooth, Inerta-coated plate). Flagged symbols indicate the first test in a series.

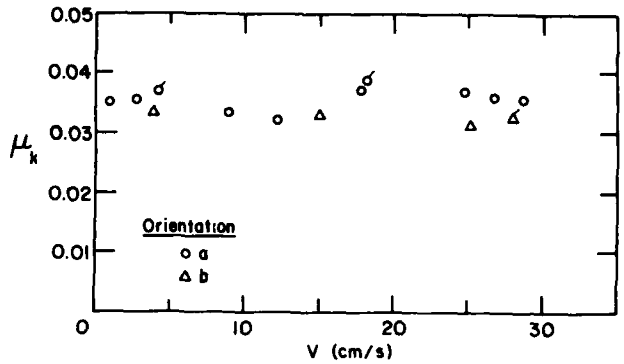


Figure 8. Test results with columnar ice on wetted, smooth, Inerta-coated plate (tests 321–335). Flagged symbols indicate the first test in a series.

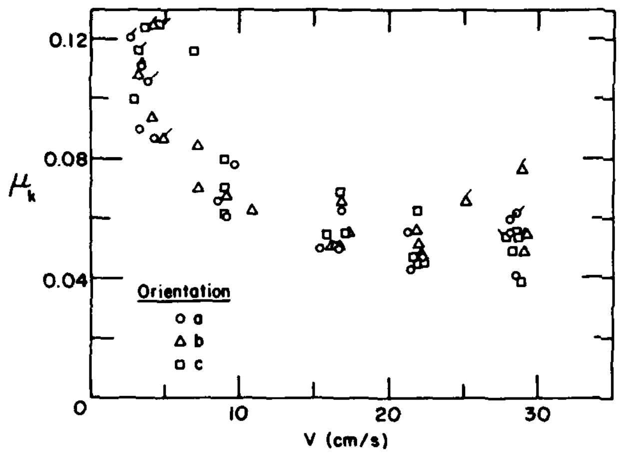


Figure 9. Test results with columnar ice on dry, roughened, Inerta-coated plate (tests 501–563). Flagged symbols indicate the first test in a series.

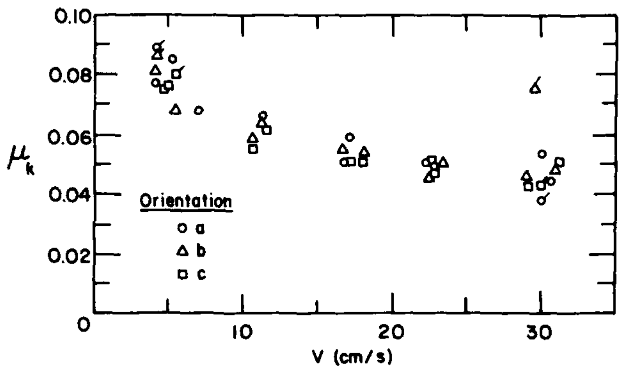


Figure 10. Test results with columnar ice on wetted, roughened, Inerta-coated plate (tests 837–873). Flagged symbols indicate the first test in a series.

ately releasing the ice sample. Furthermore, the Inerta-coated plate, roughened or smooth, and the roughened steel plate were non-wetting; the sandblasted steel plate was wetting, resulting in strong adhesion of the ice sample to the plate, which is attributed to capillary forces.

Since no effect of ice crystal orientation was noticeable, all the data for a given test surface were grouped in five subranges of velocity. The subranges were $V < 5$ cm/s, $5 < V < 12$ cm/s, $12 < V < 20$ cm/s, $20 < V < 25$ cm/s, and $V < 25$ cm/s. The average, $\overline{\mu_k}$, and standard deviation, σ_μ, of

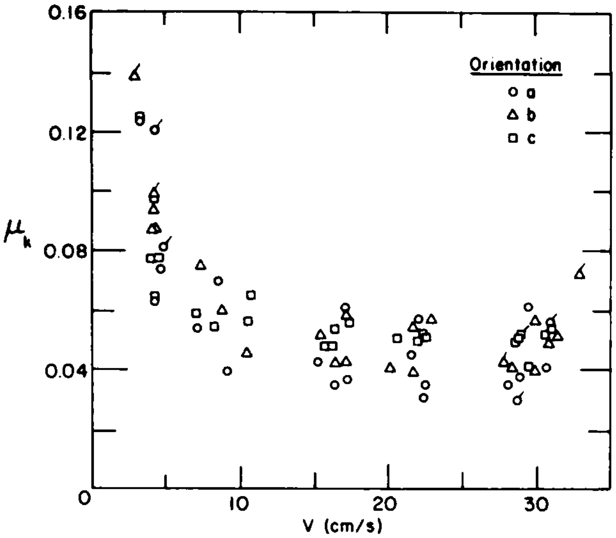


Figure 11. Test results with columnar ice on dry, roughened steel plate (tests 701–774). Flagged symbols indicate the first test in a series.

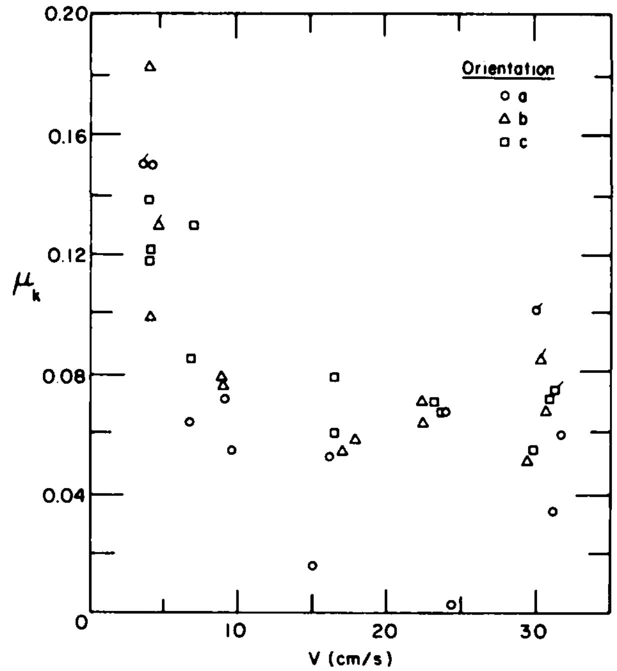


Figure 12. Test results with columnar ice on wetted, roughened steel plate (tests 801–836). Flagged symbols indicate the first test in a series.

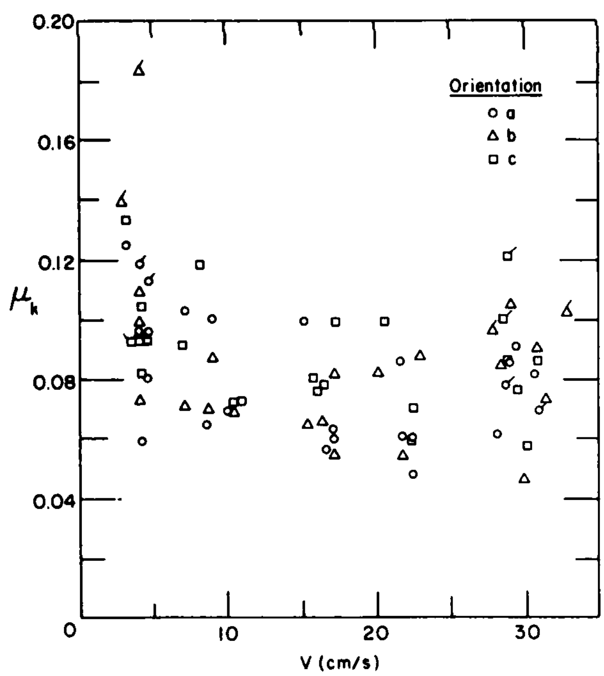


Figure 13. Test results with columnar ice on dry, sandblasted steel plate (tests 701–774). Flagged symbols indicate the first test in a series.

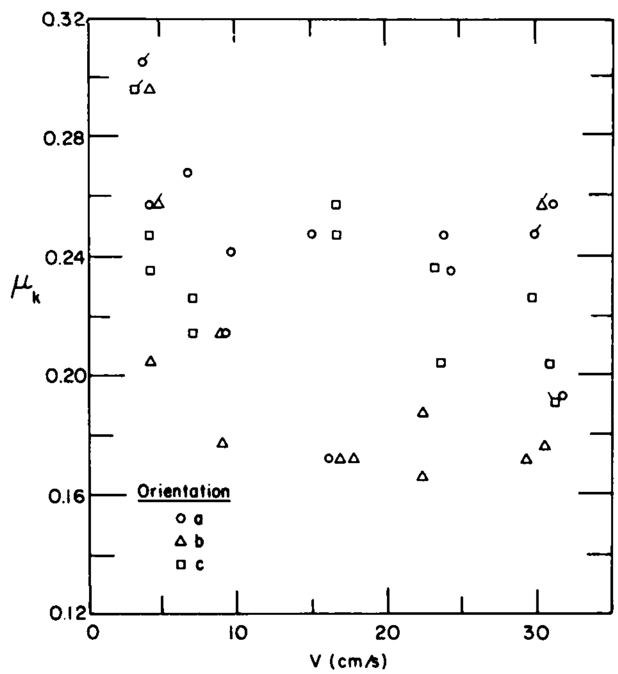


Figure 14. Test results with columnar ice on wetted, sandblasted steel plate (tests 801–836). Flagged symbols indicate the first test in a series.

Table 2. Averages of test results (columnar ice only).

		Velocity range (cm/s)				
		< 5	5–12	12–20	20–25	> 25
Smooth Inerta (0.97 μm)						
Dry	$\overline{V}$	3.0	9.5	16.1	22.2	28.7
	$\overline{\mu_k}$	0.029	0.029	0.028	0.027	0.027
	σ_μ	0.003	0.003	0.004	0.003	0.002
Wet	$\overline{V}$	2.9	9.4	15.7	—	26.7
	$\overline{\mu_k}$	0.035	0.034	0.035	—	0.035
	σ_μ	0.002	0.004	0.003	—	0.002
Roughened Inerta (3.8 μm)						
Dry	$\overline{V}$	3.8	8.4	16.4	21.8	28.5
	$\overline{\mu_k}$	0.097	0.073	0.056	0.051	0.049
	σ_μ	0.014	0.014	0.006	0.006	0.006
Wet	$\overline{V}$	4.5	10.4	17.3	22.6	30.2
	$\overline{\mu_k}$	0.077	0.062	0.054	0.049	0.048
	σ_μ	0.007	0.004	0.003	0.002	0.004
Roughened bare steel (1.1 μm)						
Dry	$\overline{V}$	4.1	8.9	16.5	21.9	29.7
	$\overline{\mu_k}$	0.090	0.058	0.048	0.047	0.047
	σ_μ	0.022	0.011	0.008	0.009	0.008
Wet	$\overline{V}$	4.1	8.4	16.5	23.2	30.5
	$\overline{\mu_k}$	0.134	0.083	0.065	0.068	0.057
	σ_μ	0.032	0.025	0.011	0.003	0.014
Sandblasted steel (7.1 μm)						
Dry	$\overline{V}$	4.1	8.9	16.5	21.9	29.7
	$\overline{\mu_k}$	0.094	0.082	0.073	0.070	0.079
	σ_μ	0.021	0.017	0.015	0.016	0.016
Wet	$\overline{V}$	4.1	8.4	16.5	23.2	30.5
	$\overline{\mu_k}$	0.248	0.214	0.211	0.212	0.205
	σ_μ	0.033	0.021	0.043	0.032	0.032

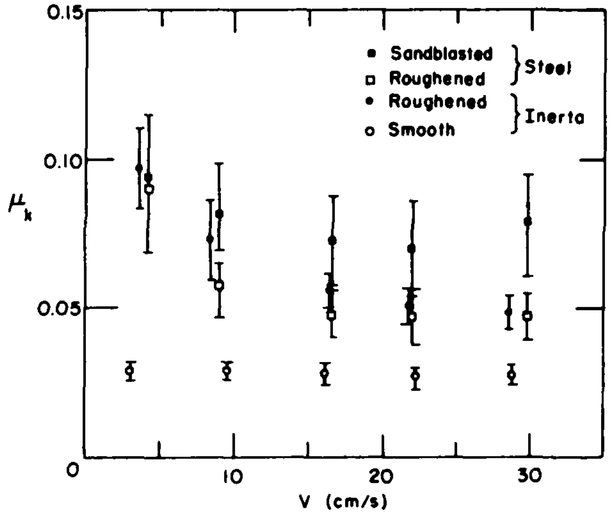


Figure 15. Effect of roughness and surface type with columnar ice on dry surfaces.

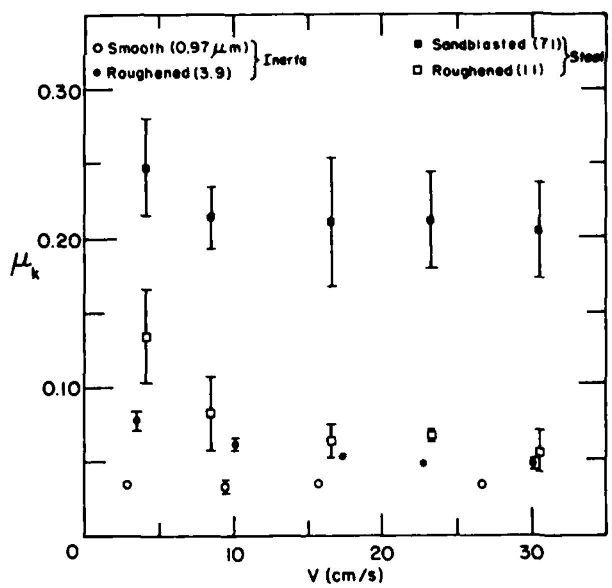


Figure 16. Effect of roughness and surface type with columnar ice on wetted surfaces.

the test results in each velocity subrange and for each test surface are presented in Table 2 and Figures 15–17.

These figures show that the Inerta-coated steel plate has a significantly lower friction coefficient than the bare steel plate of similar roughness average. Also, the friction coefficient of Inerta-coated steel is relatively unaffected by whether the surface is dry or wet, while that of the bare steel is much higher when wet than when dry, especially for the sandblasted steel plate. These results indicate that not only the magnitude but also the morphology of the roughness of a surface, as well as its surface tension characteristics when wet, greatly affect its friction coefficient with ice.

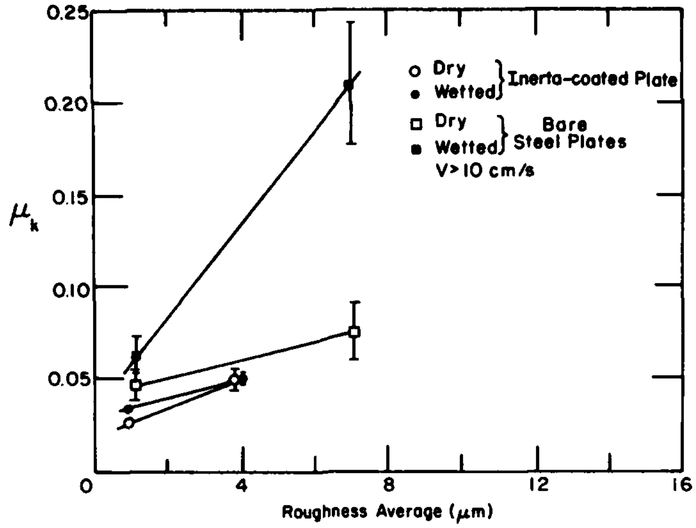


Figure 17. Effect of roughness and surface conditions on the friction coefficient.

Results summary

The main results of this limited study can be summarized as follows:

1. The kinetic friction coefficient of columnar sea ice is independent of the ice crystal orientation with respect to the test surface.

2. It is independent of normal pressure.

3. In general the friction coefficient initially decreases with increasing relative velocity and reaches a steady value at higher speeds. The initial rate of decrease appears to depend upon test surface characteristics such as roughness and surface tension.

4. The friction coefficient increases with increasing surface roughness but also depends strongly on the roughness morphology and the surface tension properties of the test surface. A water-repellent surface, such as Inerta-coated steel, has a significantly lower friction coefficient than a wetting surface of the same or even a higher roughness average.

COMPARISON WITH LABORATORY STUDY

The laboratory study of the kinetic friction coefficient of ice mentioned in the Introduction (Forland and Tatinclaux 1984, 1985) had included the two steel plates used in the field tests, as well as Inerta-coated steel with a roughness of 1.0 μm, among the material surfaces tested. The majority of the laboratory tests had been made at a velocity of about 10 cm/s and with a normal pressure of about 10 kPa. The ice samples used in the laboratory study were cut from urea-doped model ice sheets grown in the CRREL ice towing tank and were used immediately without being stored prior to the tests. Some brine drainage always occurred during the laboratory tests, and the material surface was wet at the end of each test.

The values of μ_k obtained in the laboratory and field tests for similar material surfaces and under similar test conditions for V and P are presented in Table 3. The laboratory results and the field re-

Table 3. Laboratory and field results for similar material surfaces ($V \cong$ 10 cm/s).

Material surface		*Laboratory results*	*Field results*	
			Dry surface	*Wet surface*
Inerta 160	$R = 1\ \mu$m	0.029	0.029	0.034
Steel	$R = 1.1\ \mu$m	0.192	0.058	0.083
Steel	$R = 7.1\ \mu$m	0.197	0.082	0.214

sults for wetted surfaces are in quite good agreement.

RECOMMENDATIONS ON TEST APPARATUS

The test table was built by HSVA and had not been tested prior to the tests aboard the *Polarstern*. It was found to be quite adequate for research on ice friction, but some improvements can be suggested:

1. The driving motor should be geared down so that the maximum linear speed of the test table can be limited to about 30 cm/s.
2. The precision of the motor speed control should be increased to allow easier repetition of a given speed.
3. Possible lateral motion and surge motion of the ice sample could be prevented by restraining the ice sample either by a spring or a dead weight and pulley system. This would also allow the test table to be operated in both directions to account for any slight error when leveling the table.
4. A built-in velocity measurement system could be added to the test table.
5. Bubble levels could be added to the table for checking the table level.

LITERATURE CITED

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APPENDIX A: TEST RESULTS

Table A1: Effect of wear on ice kinetic friction factor using columnar ice on a wet, smooth, Inerta-coated plate: R = 0.97 μm; θ = 8°C.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
301	6.7	917	33.5	0.0365	
302	10.7	917	34.0	0.0371	
303	11.6	917	34.4	0.0375	
304	11.8	917	33.4	0.0364	
305	12.6	917	31.8	0.0347	Crystal
306	11.7	917	31.6	0.0345	orientation a
307	12.5	917	32.5	0.0354	
308	11.6	917	31.8	0.0347	
309	13.3	917	31.4	0.0342	
310	11.6	917	31.4	0.0342	
311	12.3	917	26.8	0.0292	
312	11.4	917	27.0	0.0294	
313	11.8	917	26.4	0.0287	
314	11.9	917	27.4	0.0299	
315	12.6	917	27.0	0.0294	Crystal
316	12.2	917	26.6	0.0290	orientation b
317	11.6	917	25.8	0.0282	
318	11.3	917	25.8	0.0281	
319	11.5	917	26.3	0.0287	
320	10.9	917	25.8	0.0282	

Table A2: Effect of wear on ice kinetic friction factor using columnar ice on dry, roughened, Inerta-coated plate: R = 3.8 μm; θ ≈ -1°C.

Test No.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
601	11.9	1050	68.7	0.065	
602	10.5	1050	59.8	0.057	
603	10.9	1050	59.8	0.057	
604	9.7	1050	59.8	0.057	
605	9.6	1050	60.8	0.058	
606	10.4	1050	57.9	0.055	Crystal orientation a
607	9.7	1050	57.9	0.055	P = 10.9 kPa
608	9.5	1050	59.8	0.057	
609	10.4	1050	57.9	0.055	
610	10.5	1050	56.9	0.054	

Table A3. Friction test results for granular ice on dry, initial, Inerta-coated plate: R = 0.97 μm; θ ≈ 0.1°C.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Normal pressure (kPa)
201	4.7	917.3	22.3	0.024	
202	10.7	917.3	26.1	0.028	12.7
203	16.0	917.3	21.8	0.024	
204	3.2	1015.3	31.9	0.031	
205	7.1	1015.3	28.2	0.028	13.0
206	17.9	1015.3	26.0	0.026	
207	4.2	1039.9	27.5	0.026	
208	7.0	1039.9	27.9	0.027	13.3
209	18.3	1039.9	25.6	0.025	
210	3.2	1020.2	26.8	0.026	
211	6.2	1020.2	26.6	0.026	13.0
212	20.9	1020.2	23.0	0.023	
213	4.1	1035.0	26.4	0.025	
214	7.1	1035.0	27.7	0.027	9.9
215	18.0	1035.0	26.1	0.025	
216	17.5	1025.2	27.7	0.027	
217	8.8	1026.2	27.9	0.027	12.2
218	4.7	1025.2	29.2	0.028	
219	4.2	1054.6	28.7	0.027	
220	7.1	1054.6	28.2	0.027	7.0
221	17.8	1054.6	28.1	0.027	

Table A4. Friction test results for columnar ice on dry, initial, Inerta-coated plate: R = 0.97 μm.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
401	2.3	976	27.6	0.0283	Crystal orientation a
402	22.9	976	23.7	0.0243	P = 10.8 kPa
403	10.6	976	26.4	0.0270	θ = +1.5°C
404	29.5	976	23.9	0.0245	
405	11.5	976	26.6	0.0272	
407	21.6	964	26.2	0.0271	Crystal orientation b
408	8.8	964	29.3	0.0304	
409	2.7	964	30.3	0.0314	P = 13.8 kPa
410	16.8	964	30.5	0.0316	θ = +1.5°C
411	11.5	964	29.9	0.0310	
421	1.9	1005	32.8	0.0326	Crystal orientation b
422	27.6	1005	30.4	0.0303	P = 10.8 kPa
423	16.3	1005	31.7	0.0316	θ = −1°C
424	9.4	1005	32.8	0.0326	Light snow
425	20.9	1005	33.5	0.0333	
426	27.7	986	28.2	0.0286	Crystal orientation a
427	3.1	986	32.4	0.0329	P = 13.8 kPa
428	22.4	986	30.1	0.0305	θ = −1°C
429	15.6	986	31.7	0.0322	Light snow
430	7.0	986	32.5	0.0329	
431	28.4	966	27.3	0.0282	Crystal orientation a
432	3.3	966	26.4	0.0273	P = 16.1 kPa
433	10.5	966	27.2	0.0282	θ = −1°C
434	22.6	966	24.2	0.0250	Light snow
435	15.6	966	25.1	0.0259	
436	2.5	966	26.5	0.0274	Crystal orientation c
437	30.1	966	27.5	0.0284	P = 14.9 kPa
438	16.3	966	26.6	0.0275	
439	8.8	966	27.5	0.0284	
440	22.5	966	25.6	0.0265	
441	28.5	986	24.2	0.0245	Crystal orientation c
442	3.3	986	26.5	0.0269	P = 13.5 kPa
443	17.2	986	23.8	0.0241	
444	8.7	986	26.0	0.0263	
445	22.6	986	24.5	0.0248	
446	4.7	971	24.7	0.0254	Crystal orientation a
447	29.0	971	24.8	0.0255	P = 14.6 kPa
448	8.7	971	24.9	0.0256	
449	22.4	971	23.7	0.0244	
450	15.1	971	23.8	0.0245	

Table A5. Friction test results for columnar ice on wetted, initial, Inerta-coated plate: R = 0.97 μm; θ = 7 to 10°C.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
321	4.1	917	33.7	0.037	Crystal orientation a
322	24.8	917	33.6	0.037	P = 11.1 kPa
323	26.8	917	33.3	0.036	
324	0.84	917	32.1	0.035	
325	17.7	917	34.2	0.037	
326	28.0	907.4	29.6	0.0326	Crystal orientation b
327	3.9	907.4	30.3	0.0334	P = 16.2 kPa
328	14.9	907.4	30.1	0.0331	
329	25.1	907.4	28.5	0.0314	
331	18.1	918	35.5	0.0387	Crystal orientation a
332	28.6	918	32.8	0.0357	
333	2.6	918	32.6	0.0355	
334	8.8	918	30.9	0.0337	
335	12.2	918	29.4	0.0320	

Table A6. Friction test results for columnar ice on a dry, roughened, Inerta-coated plate: R = 3.9 μm; θ = -1°C.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
501	28.1	986	58.7	0.060	Crystal orientation a
502	3.4	986	109.9	0.112	P = 13.6 kPa
503	21.3	986	42.1	0.043	
504	9.0	986	60.5	0.061	
505	16.5	986	48.9	0.050	
506	28.8	986	76.0	0.077	Crystal orientation b
507	3.3	986	111.8	0.113	P = 15.2 kPa
508	21.9	986	51.6	0.052	
509	9.0	986	67.3	0.068	
510	16.0	986	50.3	0.051	
511	3.0	986	114.5	0.116	Crystal orientation c
512	28.1	986	48.7	0.049	P = 12.6 kPa
513	16.9	986	54.4	0.055	
514	8.9	986	69.4	0.070	
515	22.3	986	46.3	0.047	
516	4.1	961.4	120.1	0.125	Crystal orientation b
517	29.0	961.4	47.1	0.049	P = 13.7 kPa
518	10.8	961.4	60.8	0.063	
519	22.0	961.4	44.9	0.047	
520	16.5	961.4	49.5	0.051	
521	2.6	961.4	116.4	0.121	Crystal orientation a
522	28.4	961.4	39.2	0.041	P = 14.8 kPa
523	15.5	961.4	48.5	0.050	
524	22.1	961.4	44.7	0.047	
525	8.6	961.4	63.4	0.066	

Table A6 (cont'd).

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
526	27.7	961.4	52.2	0.054	Crystal orientation c
527	3.6	961.4	119.3	0.124	P = 13.7 kPa
528	21.5	961.4	44.7	0.047	
529	7.0	961.4	111.8	0.116	
530	15.7	961.4	52.2	0.054	
531	25.2	956.5	63.4	0.066	Crystal orientation b
532	3.2	956.5	104.4	0.109	P = 14.2 kPa
533	17.2	956.5	52.2	0.055	
534	7.2	956.5	67.1	0.070	
535	22.0	956.5	44.7	0.047	
536	4.1	956.5	119.3	0.125	Crystal orientation c
537	28.7	956.5	37.3	0.039	P = 14.8 kPa
538	8.8	956.5	59.6	0.062	
539	16.1	956.5	48.5	0.051	
540	22.2	956.5	44.7	0.047	
541	28.6	956.5	59.6	0.062	Crystal orientation a
542	3.2	956.5	85.7	0.090	P = 15.9 kPa
543	22.0	956.5	42.9	0.045	
546	3.9	951.6	101.0	0.106	Crystal orientation a
547	28.0	951.6	52.0	0.055	P = 15.9 kPa
548	9.6	951.6	74.6	0.078	
549	16.8	951.6	59.8	0.063	
550	21.1	951.6	52.0	0.055	
551	4.2	951.6	82.4	0.087	
552	28.5	951.6	51.0	0.054	Crystal orientation c
553	2.9	951.6	95.2	0.100	P = 18.0 kPa
554	16.6	951.6	65.7	0.069	
555	21.8	951.6	59.8	0.063	
556	8.9	951.6	76.5	0.080	
557	28.4	951.6	52.0	0.055	
558	4.1	951.6	89.3	0.094	Crystal orientation b
559	29.2	951.6	52.0	0.055	P = 16.5 kPa
560	7.1	951.6	79.5	0.084	
561	16.7	951.6	62.8	0.066	
562	21.8	951.6	54.0	0.057	
563	4.9	951.6	82.4	0.087	

Table A7. Friction test results for columnar ice on a dry, roughened, Inerta-coated plate: $R = 3.9$ µm; $\theta = 0°C$.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
564	3.0	564	56.9	0.101	Crystal orientation a
565	29.2	564	—	—	P = 9.78 kPa
566	17.0	564	34.3	0.061	
567	6.8	564	42.2	0.075	
568	21.0	564	—	—	
569	29.1	564	26.5	0.047	
570	4.9	564	52.0	0.092	Crystal orientation b
571	28.5	564	32.4	0.057	P = 8.06 kPa
572	6.8	564	45.1	0.080	
573	21.8	564	33.4	0.059	
574	16.0	564	35.3	0.063	
575	3.3	564	48.1	0.085	
576	29.1	564	41.2	0.073	Crystal orientation c
577	4.8	564	51.0	0.090	P = 8.39 kPa
578	17.4	564	32.4	0.057	
579	22.0	564	31.4	0.056	
580	7.4	564	41.2	0.073	
581	28.0	564	26.5	0.047	
582	28.2	589	38.3	0.065	Crystal orientation b
583	4.1	589	51.0	0.087	P = 7.25 kPa
584	21.0	589	33.4	0.057	
585	8.7	589	42.2	0.072	
586	16.8	589	34.3	0.059	
587	27.8	589	29.4	0.050	
588	3.9	589	66.7	0.113	Crystal orientation c
589	29.6	589	27.5	0.047	P = 8.41 kPa
590	16.5	589	30.4	0.052	
591	10.8	589	33.4	0.057	
592	21.2	589	26.5	0.045	
593	4.2	589	48.1	0.082	
594	29.0	589	26.5	0.045	Crystal orientation a
595	4.1	589	52.0	0.088	P = 8.41 kPa
596	16.9	589	28.4	0.048	
597	22.2	589	26.5	0.045	
598	7.1	589	35.3	0.060	
599	27.8	589	26.5	0.045	

Table A8. Friction test results for columnar ice on wetted, roughened, Inerta-coated plate: R = 3.9 μm; θ ≈ 0.5°C.

Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	Test conditions
837	5.3	692	58.9	0.085	Crystal orientation a
838	30.1	692	37.3	0.054	P = 15.0 kPa
839	17.2	692	41.2	0.059	
840	11.3	692	46.1	0.066	
841	22.3	692	34.3	0.050	
842	4.1	692	53.0	0.077	
843	29.5	692	52.0	0.075	Crystal orientation b
844	4.1	692	55.9	0.081	P = 15.7 kPa
845	11.3	692	44.1	0.064	
846	23.3	692	35.3	0.051	
847	18.1	692	37.3	0.054	
848	30.9	692	33.4	0.048	
849	29.9	692	29.4	0.043	Crystal orientation c
850	4.6	692	52.0	0.075	P = 15.7 kPa
851	18.0	692	35.3	0.051	
852	22.7	692	32.4	0.047	
853	10.6	692	38.3	0.055	
854	29.1	692	29.4	0.043	
855	5.4	697	55.9	0.080	Crystal orientation c
856	31.1	697	35.3	0.051	P = 15.1 kPa
857	22.5	697	35.3	0.051	
858	11.5	697	43.2	0.062	
859	17.2	697	35.3	0.051	
860	4.8	697	53.0	0.076	
861	30.0	697	26.5	0.038	Crystal orientation a
862	4.2	697	61.8	0.089	P = 15.4 kPa
863	22.7	697	34.3	0.049	
864	7.0	697	47.1	0.068	
865	16.8	697	35.3	0.051	
866	30.7	697	31.4	0.045	
867	4.2	697	60.8	0.087	Crystal orientation b
868	29.0	697	32.4	0.046	P = 16.2 kPa
869	16.7	697	38.3	0.055	
870	10.6	697	41.2	0.059	
871	10.6	697	41.2	0.059	
872	22.3	697	32.4	0.046	
873	5.4	697	47.1	0.068	

Table A9. Friction test results for columnar ice on dry, bare steel plates: $\theta = -2.5°C$.

			R = 7.1 µm		R = 1.1 µm		
Test no.	V (cm/s)	N+W (N)	T (N)	μ_k	T (N)	μ_k	Test conditions
701	4.2	693	82.0	0.118	83.5	0.121	Crystal orientation a
702	28.9	693	59.6	0.086	26.1	0.038	P = 15 kPa
703	15.2	693	68.6	0.099	29.8	0.043	
704	7.1	693	71.6	0.103	37.3	0.054	
705	21.6	693	59.6	0.086	31.3	0.045	
706	3.3	693	86.5	0.125	85.7	0.124	
707	28.8	693	83.5	0.121	35.8	0.052	Crystal orientation c
708	3.2	693	92.4	0.133	86.5	0.125	P = 15.3 kPa
709	8.2	693	82.0	0.118	37.3	0.054	
710	20.6	693	68.6	0.099	35.8	0.052	
711	17.3	693	68.6	0.099	38.8	0.056	
712	28.7	693	59.6	0.086	35.8	0.052	
713	2.9	693	95.5	0.139	95.5	0.138	Crystal orientation b
714	28.3	693	58.2	0.084	28.4	0.041	P = 14.6 kPa
715	15.5	693	44.7	0.065	35.8	0.052	
716	7.2	693	49.2	0.071	52.2	0.075	
717	21.6	693	--	--	37.3	0.054	
718	4.1	693	50.7	0.073	65.6	0.095	
719	27.8	687	65.6	0.096	28.9	0.042	Crystal orientation b
720	4.1	687	74.6	0.109	59.6	0.087	P = 15.2 kPa
721	10.4	687	47.7	0.069	31.3	0.046	
722	21.7	687	37.3	0.054	26.9	0.039	
723	17.2	687	37.3	0.054	29.8	0.043	
724	29.9	687	31.3	0.046	27.6	0.040	
725	28.7	687	53.7	0.078	20.9	0.030	Crystal orientation a
726	4.7	687	55.1	0.080	--	--	P = 15.2 kPa
727	16.6	687	38.7	0.056	23.8	0.035	
728	22.5	687	32.8	0.048	23.8	0.035	
729	9.0	687	68.6	0.100	26.9	0.039	
730	28.1	687	41.8	0.061	23.8	0.035	
731	4.7	687	65.6	0.096	50.7	0.074	
732	4.2	687	71.6	0.104	--	--	Crystal orientation c
733	29.5	687	52.2	0.076	28.4	0.041	P = 15.2 kPa
734	15.8	687	55.1	0.080	32.8	0.048	
735	10.5	687	49.2	0.072	38.7	0.056	
736	22.0	687	41.8	0.061	34.3	0.050	
737	4.2	687	62.6	0.091	67.1	0.098	
738	4.1	684	125.3	0.183	68.1	0.099	Crystal orientation b
739	29.1	684	71.6	0.105	38.8	0.057	P = 17.1 kPa
740	9.0	684	59.6	0.087	--	--	
741	17.2	684	55.1	0.081	40.2	0.059	
742	22.9	684	59.7	0.087	38.7	0.057	
743	4.1	684	64.2	0.094	59.6	0.087	
744	28.6	684	68.6	0.100	34.3	0.050	Crystal orientation c
745	7.0	684	62.6	0.091	40.2	0.059	P = 16.7 kPa
746	22.5	684	47.6	0.070	35.8	0.052	
747	4.1	684	62.7	0.092	--	--	
748	16.1	684	52.2	0.076	32.8	0.048	
749	30.7	684	38.7	0.057	35.8	0.052	

Table A9 (cont'd).

Test no.	V (cm/s)	N+W (N)	R = 7.1 μm T (N)	R = 7.1 μm μ_k	R = 1.1 μm T (N)	R = 1.1 μm μ_k	Test conditions
750	4.7	684	77.5	0.113	55.1	0.081	Crystal orientation a
751	29.4	684	62.6	0.091	41.8	0.061	P = 15.5 kPa
752	17.1	684	43.3	0.063	41.8	0.061	
753	8.6	684	44.7	0.065	47.7	0.070	
754	21.9	684	41.8	0.061	38.7	0.057	
755	4.2	684	40.2	0.059	43.3	0.063	
756	4.0	692	62.6	0.091	53.7	0.078	Crystal orientation c
757	30.9	692	59.7	0.086	37.3	0.054	P = 15.7 kPa
758	10.8	692	50.7	0.073	44.6	0.065	
759	22.3	692	40.2	0.058	35.8	0.052	
760	16.4	692	53.7	0.078	37.3	0.054	
761	4.2	692	56.7	0.082	44.7	0.065	
762	30.9	692	47.7	0.069	38.7	0.056	Crystal orientation a
763	4.1	692	65.6	0.095	53.7	0.078	P = 15.3 kPa
764	17.1	692	41.8	0.060	24.6	0.036	
765	22.4	692	41.8	0.060	21.4	0.031	
766	10.0	692	47.7	0.069	—	—	
767	30.6	692	56.7	0.082	28.4	0.041	
768	32.8	495	50.7	0.102	35.8	0.072	Crystal orientation b
769	30.8	692	62.6	0.090	34.3	0.050	P = 15.3 kPa
770	4.0	692	68.6	0.099	—	—	
771	20.2	692	56.7	0.082	28.4	0.041	
772	16.5	692	44.7	0.065	29.8	0.043	
773	8.7	692	47.7	0.069	41.8	0.060	
774	31.4	692	50.7	0.073	35.8	0.052	

Table A10. Friction test results for columnar ice on wetted, bare steel plates: θ = −0.5°C.

Test no.	V (cm/s)	N+W (N)	R = 7.1 μm T (N)	R = 7.1 μm μ_k	R = 1.1 μm T (N)	R = 1.1 μm μ_k	Test conditions
801	3.6	692	210.9	0.305	104.0	0.150	Crystal orientation a
802	31.3	692	177.6	0.257	23.5	0.034	P = 16.3 kPa
803	15.0	692	170.7	0.247	10.8	0.016	
804	24.2	692	162.8	0.235	2.0	0.003	
805	9.5	692	166.8	0.241	37.3	0.054	
806	6.7	692	185.4	0.268	44.1	0.064	
807	30.2	692	177.6	0.257	58.9	0.085	Crystal orientation b
808	4.0	692	204.0	0.295	125.6	0.182	P = 16.1 kPa
809	22.3	692	129.5	0.187	49.1	0.071	
810	8.9	692	122.6	0.177	53.0	0.077	
811	16.9	692	118.7	0.172	37.3	0.054	
812	29.3	692	118.7	0.172	35.3	0.051	

Table A10 (cont'd). Friction test results for columnar ice on wetted, bare steel plates: θ = -0.5°C.

Test no.	V (cm/s)	N+W (N)	R = 7.1 μm T (N)	R = 7.1 μm μ_k	R = 1.1 μm T (N)	R = 1.1 μm μ_k	Test conditions
813	4.0	692	204.0	0.295	95.2	0.138	Crystal orientation c
814	30.8	692	141.3	0.204	50.0	0.072	P = 16.5 kPa
815	16.5	692	170.7	0.247	54.9	0.079	
816	6.9	692	148.1	0.214	89.3	0.129	
817	23.5	692	141.3	0.204	47.1	0.068	
818	4.1	692	162.8	0.235	83.4	0.121	
819	31.2	692	132.4	0.191	52.0	0.075	Crystal orientation c
820	4.0	692	170.7	0.247	81.4	0.118	P = 15.3 kPa
821	23.1	692	162.8	0.236	49.1	0.071	
822	6.9	692	156.0	0.226	58.9	0.085	
823	16.5	692	177.6	0.257	41.2	0.060	
824	29.7	692	156.0	0.226	38.3	0.055	
825	29.9	692	170.7	0.247	69.7	0.101	Crystal orientation a
826	4.1	692	177.6	0.257	104.0	0.150	P = 15.7 kPa
827	16.1	692	118.7	0.172	50.0	0.072	
828	23.8	692	170.7	0.247	47.1	0.068	
829	9.2	692	148.1	0.214	50.0	0.072	
830	31.6	692	133.4	0.193	41.2	0.060	
831	4.6	692	177.6	0.257	89.3	0.129	Crystal orientation b
832	30.5	692	122.6	0.177	47.1	0.068	P = 15.3 kPa
833	22.4	692	114.8	0.166	44.1	0.064	
834	17.8	692	118.7	0.172	40.2	0.058	
835	8.8	692	148.1	0.214	54.9	0.079	
836	4.1	692	141.3	0.204	68.7	0.099	

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Tatinclaux, Jean-Claude
Field tests of the kinetic friction coefficient of sea ice / by Jean-Claude Tatinclaux and David Murdey. Hanover, N.H.: Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1985.
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